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Evaluation of Transfer Space Efficiency of Metro Stations in Renovation Projects Using Virtual Wayfinding Tasks and User Satisfaction Surveys

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ABSTRACT
Recently, more and more older metro stations in China need renovation work to be updated to meet the passenger demand of the new era. Practices show that especially the spatial problems need to be identified in the early design phase in renovation projects (since architectural space is the basic foundation for all the upcoming designs such as signage systems, lighting, interior decoration and so on) to know in which spatial design aspects the station needs to maintain or improve. In this work, we have established a scientific and systematic transfer space quality evaluation system. Using this evaluation system and through remote virtual wayfinding experiments on three metro stations in Beijing, we compared the wayfinding efficiency and questionnaire survey results from the station's blank spatial models with real-life wayfinding and survey results. In the end, it was possible to identify the aspects of the station's spatial quality that need improvement. The proposed method can help designers gain a more concrete idea of the indoor space of their to-be-renovated station building in regard to passenger wayfinding efficiency and user satisfaction, and make optimisations in the early planning phase.

KEYWORDS
simulated wayfinding; wayfinding efficiency evaluation; metro station renovation; spatial layout.

1. INTRODUCTION

Although urban transport has been developing and constructing continuously, rail transit lines are still under great pressure from passenger flow. For passengers, efficiency problems such as queuing time, long transfer distance, complex transfer path and long waiting time persist [1-4]. In addition, security hazards such as congestion and high loads of facilities also exist. Under these situations, passengers tend to feel agitated, irritable or negative in the transfer process, thus leading to a poor travel experience. With the integrative development of rail and urban transport, urban rail transit constructions in China have shifted from the rapid and expansive development mode to high-quality development, focusing on quality, efficiency, integration and innovation. At present, Beijing's urban rail construction is still in the early stage of the 3rd phase (2022-2027). It is important to understand how to realise high-quality transfer in rail transit to gain an ideal transfer efficiency in the transportation system. Especially nowadays, numerous existing metro stations have been renovated to meet the demands of the new era, where the utmost attention should be given to the spatial flexibility, applicability and efficiency of metro transfer from the beginning of the planning and construction phase to achieve optimal results.

Metro transfer spaces are critical components of urban transportation systems, facilitating the movement of passengers between different lines and modes of transport. The quality of these spaces often impacts passenger experience and operational efficiency. However, one of the main challenges in metro station renovation projects is to understand the advantages and disadvantages of the existing spatial design, namely, how the "where", "what" and "how" of the existing space influence the transfer space efficiency. Since the original architectural space is the foundation for all the other upcoming designs (other attached elements such as interior design and signage system design), it is important to focus on evaluating and understanding the quality of existing metro transfer spaces, in both the architectural space itself as well as its attached elements.

1.1 Wayfinding efficiency

Wayfinding efficiency is one of the most important components in evaluating the quality of design and functionality of transportation buildings' complex environments. Effective wayfinding systems enhance user experience by reducing confusion and improving navigation, which is essential for maintaining high levels of service. In wayfinding experiments, participants are often given the task of finding a certain destination to observe the wayfinding efficiency. The common objective and quantitative task performance metrics for evaluating wayfinding efficiency include [5]:

- Time taken: The duration required to reach a destination is a primary measure of efficiency [6-7].
- Distance travelled: The total distance covered during navigation can indicate the directness of the route taken.
- Number of errors: This includes wrong turns or backtracking, which can highlight navigation difficulties [8].

There are also different subcategories of the metric "time taken" inside multimodal transportation hubs. In many cases, the time taken refers to transfer time. Cheng et al. explored the impact of transfer on the choice of urban rail transit routes, introduced the perceived transfer time of passengers, and modelled it under different resolutions. The study of the Shanghai Metro showed that the perceived transfer time reflected the transfer impact more accurately, and the transfer weight increased nonlinearly [9]. Yan et al. proposed a framework for estimating transfer time and extracting transfer route distribution by using WIFI probe data [10]. Wang, Y. et al. explored the mass passenger flow control scheme of T-type metro stations through theoretical analysis and numerical simulation. By simulating the transfer passenger flow during peak hours, they found that the flow can be more orderly, the transportation efficiency can be higher, and the station congestion can be effectively alleviated by adjusting and controlling the speed, direction and path of passengers and optimising the layout of transfer space facilities [11]. Lachapell and Boisjoly broke down the transit time into access time, wait time, total travel time, overall trip speed and per cent of trip time spent in access and wait (off-vehicle time) to gain a deeper understanding of how different transit users spend their transfer time [12].

1.2 Spatial design factors and user satisfaction in transfer hubs

Field research shows that architectural space design has an important impact on passenger satisfaction during transfer. There are research works that have conducted in-depth research on the evaluation of user satisfaction in public transit spaces. For instance, to evaluate the transfer space quality of the built environment, Wu divided the specific evaluation into three indicator layers (interchange facilities, environmental quality and design features) and six guideline layers (interchange time, interchange distance, interchange safety, interchange comfort, interchange information and interchange space) [13]. Marinov et al. consider information, infrastructure, design to make passengers comfortable, accessibility, peak time performance and capacity to be relevant for customer service in transportation stations [14]. Huang used path analysis software to evaluate the layout of the internal space of urban metro hubs, the organisation of transfer flow lines, the connection of transfer facilities and transfer capacity facilities for element configuration evaluation and transfer flow line assessment [15]. Sun Cheng et al. used advanced eye-tracking equipment to understand the real thoughts and ideas of passengers in the wayfinding process and, as an important factor affecting the wayfinding of passengers in complex large-scale complexes, provided ideas for further optimising the planning and layout of large-scale commercial buildings [16]. Obsie et al. studied users' views through 18 quality attributes by taking Addis Ababa light rail transit as an example and conducting factor analysis using the ordered logic model. They found that seven key factors, including safety guarantee, affect users' satisfaction with transfer upon principal component factor analysis. The importance of these factors varied with the socio-economic and travel characteristics of users. Rush-hour, high-income, short-trip and shopping passengers had negative perceptions of congestion, while long-distance travel, regular users, workers and students had positive evaluations of some system attributes [17]. Sun et al. sorted the TOD (transit-oriented design) evaluation methods around rail transit stations into three categories: TOD index, node-location model and data envelopment analysis model. Multidimensional indexes are aggregated as a single value for evaluation with the TOD index method; the node-location model emphasises transportation, land use, balance and expansion factors. Limited studies pre-evaluate sites under construction or planning. The index system is constructed, the site is chosen, and the transfer environment is optimised in this paper by evaluating the TOD level of the site [18]. It was also discovered that the completeness of spatial knowledge significantly affects wayfinding performance, with better-informed passengers navigating more efficiently and experiencing less anxiety [19]. Improved wayfinding maps that align with the actual environment enhance route planning strategies and reduce wayfinding time, leading to more consistent and satisfactory user experiences [20-22]. Studies have shown that well-designed spaces can enhance user wayfinding and overall satisfaction [23-27]. It is also claimed that clear visual elements such as landmarks, architectural spaces and signage are decisive for improving wayfinding efficiency [28-29]. Passengers will be guided by these visual indicators and find their destinations on their own. Xia et al. quantitatively analysed the visual system of cultural elements in metro stations, discussed the visual responses of different types of passengers and summarised the rules of metro space design, providing a theoretical basis for improving the quality of transfer space based on eye movement test data and questionnaire survey [30]. Similar research that concentrates on visuo-spatial attention during wayfinding can also be found [31-33].

1.3 Aim and objective

From the literature review, the authors found that most studies are based on quantitative analysis, and only a few draw comprehensive conclusions based on quantitative evaluation and qualitative user satisfaction data. It is also relatively rare to combine architectural space-related analysis with the above-mentioned data, thus providing fewer opportunities for designers to understand how to improve the spatial quality (both the space itself as well as other attached elements) using architectural measures of the transfer space in renovation or future construction projects.

This paper is dedicated to creating a scientific and systematic evaluation system for metro station transfer space quality. This system aims to pinpoint areas in metro station spatial design that need improvement, with a particular focus on how the original architectural space affects wayfinding efficiency and user satisfaction. Additionally, it seeks to support designers during the early planning of renovation projects, allowing them to optimise designs according to passenger requirements. Therefore, the research questions are as follows.

How does the original architectural space influence wayfinding efficiency and user satisfaction?

Which spatial design elements are critical for transfer space quality?

These questions are answered by developing a scientific and comprehensive transfer space evaluation system through a combination of remote experiment methods and questionnaire surveys. Wayfinding experiments are carried out using virtual blank models of metro station transfer spaces. This is to study how the original architectural space impacts wayfinding efficiency and user satisfaction. The results are then contrasted with those from real-life metro station transfer spaces, which include elements such as interior decoration, signage and advertisements. This comparison helps to understand the functions of these additional elements.

The expected outcomes include clear identification of spatial design aspects in metro stations that need improvement, offering practical guidance for designers in renovation projects by understanding which design elements are effective and which need adjustment. Designers can enhance transfer space quality, boosting wayfinding efficiency and user satisfaction, thus improving the overall travel experience for passengers. The proposed evaluation system can also be applied in the early stage of rail transit planning and design to assess and redesign transfer space quality. These play important auxiliary roles both in the design and operation of metro stations and in cost reduction as well as efficiency improvement during rail transit construction [34].

This paper consists of five parts. The first part sets forth the current situation of transfer space and the efforts made by experts and scholars to solve problems concerning the quality of metro transfer space. The second part introduces the research method and technical application of this paper. The third part elaborates on the collection of valuable passenger information in a simulated transfer via a wayfinding experiment. The fourth part analyses the factors influencing the transfer process obtained at the end of the experiment and establishes the scientific transfer space evaluation system. In the fifth and sixth parts, the results of the study are summarised, and the prospects for future research are discussed.

2. RESEARCH METHODOLOGY

This study aimed to explore the impact of the interchange space environment on passenger wayfinding [35] through field research, with Haidian Huangzhuang Station in Zhongguancun West, Zhongguancun Station and Suzhou Street Station Line 10 as the experimental locations. The Suzhou Street Station is not connected to the metro station of Line 16, and Line 10 is in normal operation. Using a questionnaire survey and a remote virtual wayfinding experimental method, we constructed an evaluation system for transfer spaces through qualitative evaluation and quantitative evaluation from two dimensions, i.e. a subjective survey and objective data. Finally, we analysed the important factors affecting the efficiency of the transfer space at metro stations and verified them through an efficiency evaluation [36-38]. To provide a reference for the evaluation of metro station transfer efficiency, the research framework is shown in *Figure 1*.

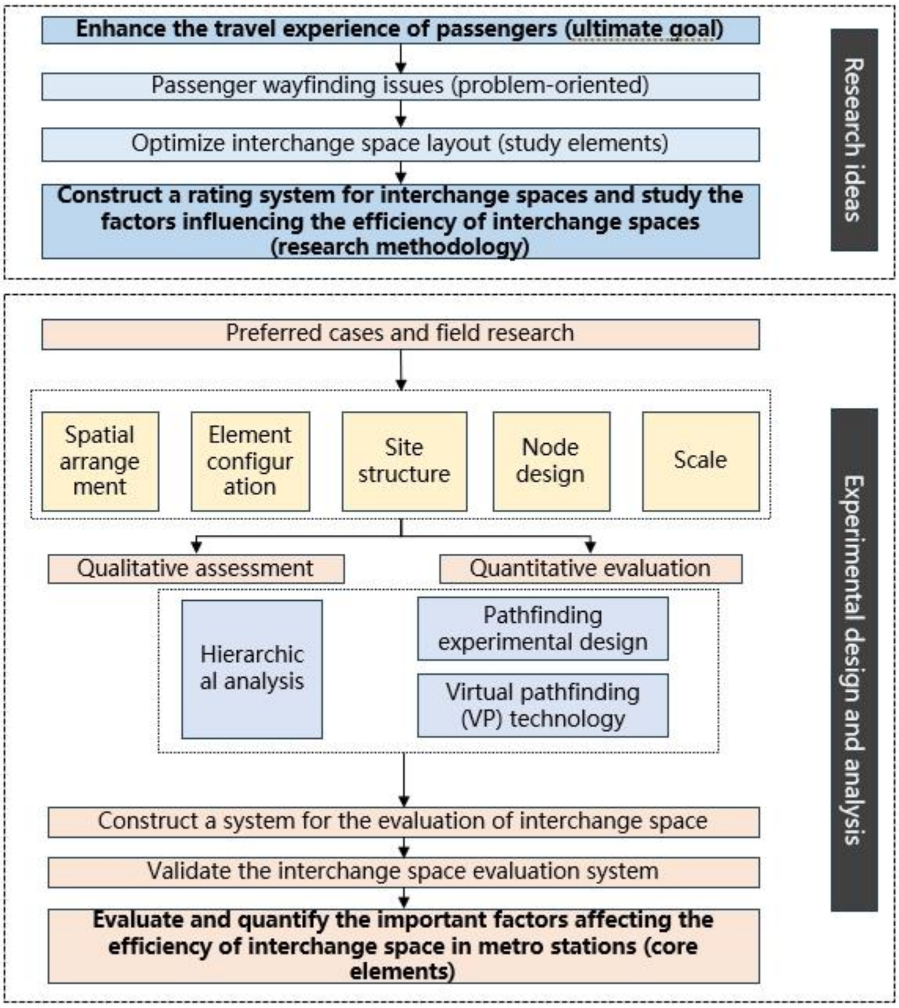

Figure 1 – Research framework

Virtual wayfinding refers to the behaviour of autonomous wayfinding by subjects in a virtual preset environment. Experimenters build a virtual three-dimensional (3D) blank model, and participants perform wayfinding tasks in the virtual environment under the guidance of experimenters with the help of experimental instruments. This technology is widely used in scientific experiments, sightseeing tours, commercial games and other fields. Simulated wayfinding is applied to 3D digital modelling, virtual reality (VR), mixed reality (MR), augmented reality (AR) and other cutting-edge technologies. Remote virtual wayfinding allows selected subjects to participate in wayfinding experiments across time and space constraints while ensuring the feasibility and scientific nature of the experiment. To a certain extent, remote virtual wayfinding experiments compensate for the limitations of virtual wayfinding experiments in the selection of subjects and can still meet the experimental conditions under special time and space requirements.

3. WAYFINDING EXPERIMENT

To facilitate the study of passenger perceptions in the original architectural space, we analysed the influence of the transfer space on passenger interchanges with blank 3D virtual models. The experimenters built a 3D model and set up a 3D simulation of the transfer experiment. Due to the fact that we wanted to focus on the influence of the original architectural space of the metro station, it was necessary to reduce the influence of other factors, such as signage and indoor decorations; only the spatial layout was expressed in the blank model with no other elements attached. The subjects used the computer mouse and keyboard to control walking within the 3D simulation software from a first-person perspective, thus simulating the entire process of passenger transfer. For comparison, the subjects were also required to watch a full video of the transfer within the real-life environment. After the experiment was complete, a questionnaire evaluation survey was conducted. The experimental data analysis was based on the subject questionnaire survey, and the experimental results were based on theoretical data and subjective questionnaires.

3.1 Case selection

In accordance with the "Beijing Urban Renewal Action Plan (2021-2025) Year" and the "Approval of the Implementation Plan of the Multi-node Public Space Renovation and Upgrading Project of Zhongguancun Street", Zhongguancun Plaza in Haidian is about to complete the overall upgrading and reconstruction. Haidian Huangzhuang Station, Zhongguancun Station and Suzhou Street Station are the three metro interchange stations around Zhongguancun Square, which bring a large flow of people to Zhongguancun Square. Therefore, it is typical to study the interchange space wayfinding of the metro Haidian Huangzhuang Station, Zhongguancun Station and Suzhou Street Station.

Haidian Huangzhuang Station

Haidian Huangzhuang Station is located at the intersection of Zhongguancun Street and Haidian South Road and Zhichun Road in Haidian District and belongs to Beijing Jinggang Metro Co. It was first opened on 19 July 2008, owing to the opening of Beijing Metro Line 10, and passed through Beijing Metro Line 4 on 28 September 2009.

Haidian Huangzhuang Station is oriented east–west to Line 10, with side platforms on the upper level and Line 10 station halls on the lower level at the east and west ends. The north–south direction of the station is Line 4, with Line 4 station halls at the north and south ends of the upper level and island platforms at the lower level, as shown in *Figure 1* and *Figure 2*. Haidian Huangzhuang Station has orange as its main colour, and the interior of the station is based on the design concept of technological rationality, which is decorated with lines of mechanical elements.

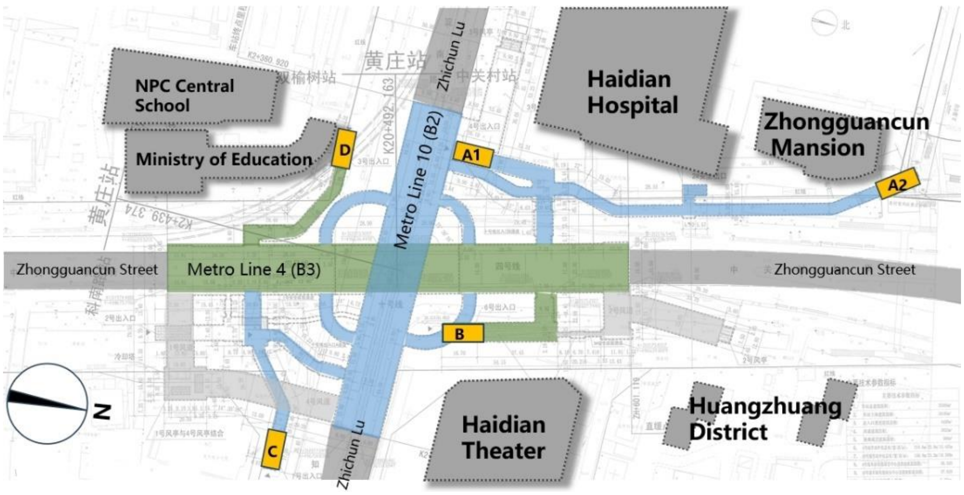

Figure 1 – Layout of Haidian Huangzhuang Station

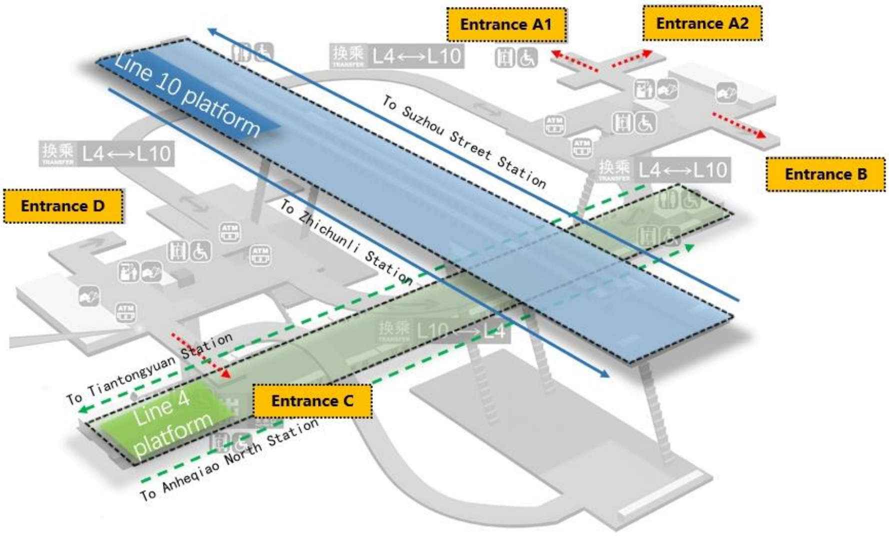

Figure 2 – Three-dimensional structure of Haidian Huangzhuang Station

There are a variety of industries and urban functions in the 500 m living circle near Haidian Huangzhuang Station, including Haidian Hospital, New Zhongguancun Shopping Centre, Leader Exhibition Shopping Centre, Haidian District People's Court and Zhongguancun Plaza in the northeast; High School attached to Peking University, Haidian Theatre and Huangzhuang Community of the Chinese Academy of Sciences in the northwest; High School attached to the People's University of China and the People's University of China in the southwest; and Hesheng Mansion and Pangaea Mansion in the southeast, Zhichunli West neighbourhood. As one of the metro stations with the largest number of interchanges [39-40] and an important metro hub in the region, Zhongguancun Plaza brings a large flow of people due to its special location.

Zhongguancun Station

The Zhongguancun metro station is located at the southern side of the intersection of North Fourth Ring West Road and Zhongguancun Road. The metro station is arranged along Zhongguancun Street in a north–south direction; it belongs to the Beijing Jinggang Metro and passes through the line for Beijing Metro Line 4, which was opened for operation on 28 September 2009.

Zhongguancun Station is a two-story underground station with a two-story underground three-span structure and an island-type platform design, with a total length of 179.9 m and a total width of 22.5 m. The main structure is constructed via the cover-digging and inverse-working methods. The first basement level is the entire station hall of the interchange type, and the second basement level is the platform level with a full-height safety gate, as shown in *Figure 3*. The Zhongguancun metro station is an ordinary metro station; the platform form is an island-type platform, and the overall presentation of commercial science and technology style is integrated with the site of high-tech industry layout elements.

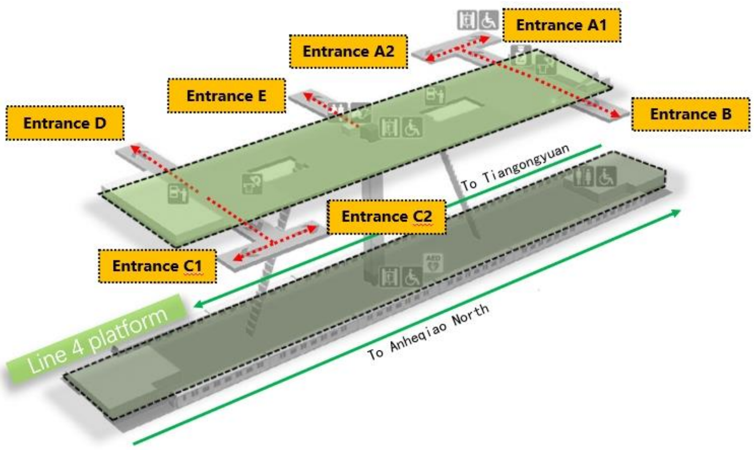

Figure 3 – Structure of Zhongguancun Station

The west side of the Zhongguancun metro station services the Dinghao Building, Founder International Building, Hailong Building, Sitong Building and Zhongguancun Plaza of the eWorld Fortune Centre; the east side services the Kechun Community, Keyu Community, Huangzhuang Community, Zhongguancun Science and Technology Trade and Electronic City; the northeast side services the Keyuan Community, the Second Primary School of Zhongguancun and the Institute of Acoustics of the Chinese Academy of Sciences; and the northwest side services Peking University and Haidian Road Community. There are more schools around the metro station, and the passengers served are mainly students in the neighbourhood, which places more pressure on the operation of the metro station.

Suzhou Street Station

The Suzhou Street metro station is located at the intersection of South Haidian Road and Suzhou Street and is an interchange station for Line 10 and Line 16. The station began operating in July 2008 due to the opening of Metro Line 10, and on 30 December 2023, it was connected to Metro Line 16. The station for Metro Line 10 runs east–west, and the station for Metro Line 16 runs north–south.

Line 10 Suzhou Street Station is a two-story underground station, and the station is located at the road intersection to bypass the various types of existing pipelines below the road surface. For the separation of the station hall, a side platform design was used, and the two ends of the two-story concealed excavation were used; the middle of a single layer of concealed excavation was used for construction. The Line 16 station for the two ends of the double-decker, the middle of a single-decker at the end of the hall, and the island-type platform station are located at the Line 10 station, as shown in *Figures 4* and *5*.

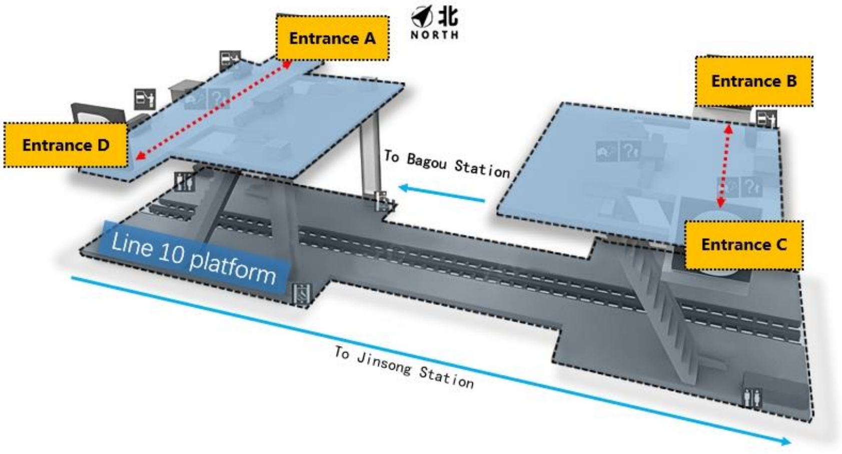

Figure 4 – Suzhou Street metro station Line 10 structure (before Line 16 access)

Figure 5 – Sectional effect of the Suzhou Street metro station

The Suzhou Street metro station services the Beijing Bayi School and National Building in the northwest direction; Shiheng Garden District, Bayi School Primary School, Haikai Mansion and Haidian District People's Court in the northeast direction; No. 24 House on Haidian South Road and China National Language Translation Bureau in the southeast direction; and the Aerospace Precision Building in the southwest direction. Suzhou Street is at the southeast corner of Zhongguancun Plaza and is one of the main sources of pedestrian flow in Zhongguancun Plaza.

3.2 Experimental design

Preferred subjects

This experiment selected subjects with a certain knowledge of spatial perception; therefore, they were required to have an educational background in architecture or related disciplines. Moreover, they should be able to skilfully operate the 3D model after simple training. 36 subjects were ultimately selected, of whom 19 were male and 17 were female, composing a relatively balanced gender distribution; the age of the subjects was between 22 and 29 years; the visual acuity of the naked eye or corrected visual acuity was better than or equal to 1.0, without colour blindness or colour weakness; they should also have strong spatial perception and normal cognitive levels.

Preparing the experiment

The experimental materials for this study were as follows.

1) A blank virtual 3D model of a specific metro station. The 3D model in the experiment expressed only the spatial layout, and the red-marked entrances and exits in the 3D model were incorrect destinations; the green-marked entrances and exits were correct, unique and the correct destinations for the simulated wayfinding experiment. During the experiment, the subjects were asked to use the remote control to simulate the process of finding a destination in a metro station.
2) Preset experimental path. This experiment simulated the process of passenger transfer, in which subjects started the wayfinding experiment from the location where they exited the metro, and the destination was the only green-marked exit. To simulate the real transfer process, the correct exit was selected based on the following characteristics.
   — The exit closest to Zhongguancun Square: Zhongguancun Square and its neighbourhood have enormous traffic flows, and the metro station entrances and exits are nodes of pedestrian flow. The goal of this study was to direct a large amount of traffic to Zhongguancun Square; therefore, the metro station closest to Zhongguancun bore the main transfer traffic, and the larger amount of traffic was representative.
   — Exit points with fewer irrelevant elements in the neighbourhood: interference from commercial facilities, decorations and other extraneous elements not only affects the wayfinding process but also affects the experimental effect to a certain extent.
   — The exit with a similar spatial layout as the other exits at this station: to ensure the normal wayfinding process and simulate the subject's thinking process when facing the intersection, we cannot choose an exit with a unique shape that can be discovered instantly.
3) Based on the above criteria, the final selection of the experimental exit was the A1 exit of the Zhongguancun metro station and the A2 exit of the Haidian Huangzhuang Station. The actual wayfinding video format requirements were as follows: a screen resolution of 1920x1080 and a screen smoothness of 30 frames per second (1080p/30fps). The length of the wayfinding video at Zhongguancun Station was 2 minutes and 31 seconds, the length of the wayfinding video at Haidian Huangzhuang Station was 3 minutes and 32 seconds, and the initial point and end point in the recorded video were the same.

Experimental steps

The entire experiment consisted of two phases: the first phase was wayfinding in the virtual 3D model. In this phase, the subjects remotely operated the virtual characters in the 3D software through their personal computers to find their way around and then independently completed the wayfinding from the start point to the end point of the model after the experimental staff introduced the experimental tasks. After completing the experiment, the subjects were required to fill out an electronic questionnaire under the guidance of the experimenter.

The second phase involved watching the actual wayfinding video. 10 minutes after the end of the first phase, the subjects were required to watch a video of the experimenter's actual wayfinding inside the metro and then complete the second questionnaire under the guidance of the experimenter. The experimenter made audio and video recordings of the entire process during the two phases. A 10-minute break between the two phases was required to prevent the results of the second phase of the experiment from being affected by the first phase of the experiment. The experimental procedure of this experiment was as follows: filling in personal information, adapting to the 3D software, determining the point of reference, operating the remote system, filling in the first questionnaire, watching the wayfinding video, filling in the second questionnaire and communicating the experimental feelings. There were a total of eight steps. The specific operational details were as follows.

1) Personal information filling. After suitable subjects were selected, the experimenter explained the purpose of the experiment, the content of the experiment and the precautions to the participants, and the participants were required to voluntarily complete the experimental informed consent form. After confirming the consent form, the experimental staff invited the subjects to provide their basic personal information and keep their information confidential.
2) 3D software adaptation. The experimenter instructed the subjects to use the computer to operate the 3D software remotely until the subjects were capable of completing wayfinding independently within the 3D software. Prior to the formal experiment, the subjects were given 1 min to acclimate to a virtual model selected by the experimenter and were able to perform simple manipulation trials within the model.
3) Determination of the point of reference. The experimenter pointed out to the subjects the reference points of the metro station wayfinding, and the subjects observed the structure of the metro station model for 1 minute and planned the wayfinding route in advance.
4) Remote system operation. After familiarising themselves with the basic operation of the model, the subjects were guided by the experimenter to complete the wayfinding experiment.

   The experimenter opened the 3D model software, set up the parameters in advance, and carried out the trial operation to ensure that the operation control virtual character could carry out normal wayfinding. The subjects needed to connect to the experimental computer remotely through a personal computer under the instructions of the experimental personnel through the 3D model of the experimental computer to carry out the pre-wayfinding process. During the pre-wayfinding process, if the subject experienced discomfort, such as dizziness, the subject guided the direction of travel, and the experimenter completed the specific wayfinding operation. After the experimental staff described the precautions for wayfinding, the subjects started the wayfinding experiment, and the experimental staff started to record video and audio at the same time.

   When the subject reached the green exit and touched the green wall model, the subject had reached the end of the wayfinding task and had completed the wayfinding experiment. If the subject could not recognise the correct wayfinding direction during the wayfinding process, the subject indicated this to the experimenter. After confirmation by the experimenter, the subject had 1 minute to look at the wayfinding model again and restart the wayfinding experiment, and this was recorded as "getting lost" once. If lost again, the above operation was repeated, and the number of lost times was recorded until the subject found the correct wayfinding exit.
5) First questionnaire completion. The experimenter made an online questionnaire in advance according to the model wayfinding situation. After the subjects finished the first wayfinding experiment in the 3D model, the experimenter presented the online questionnaire to the subjects and had them fill in the questionnaire according to their wayfinding experience in the model.
6) Watch the wayfinding video. The experimenters needed to record a real-life wayfinding video in advance that was consistent with the reference point of the model wayfinding. 5 minutes after the subjects completed the first questionnaire, they watched the recorded video of real-life wayfinding.
7) Second questionnaire completion. The experimenter prepared the second questionnaire as a control variable for reference and comparison. The content of the second questionnaire should have been consistent with that of the first questionnaire. After the subjects watched the real-life wayfinding model, they completed the second online questionnaire.
8) Communicate the experience of the experiment. After the completion of the wayfinding experiment, the subjects and the experimenters reviewed the entire process of the experiment, analysed and exchanged ideas and feelings in the process of the experiment, made a brief record of the exchange and finally ended the audiovisual recording.

The experimental steps in this study are carefully designed. The obtained data will help to gain a comprehensive exploration of how the original architectural space affects wayfinding efficiency and user satisfaction, and hence give insights on how to improve the transfer space quality of metro stations.

4. DATA ANALYSIS

In this study, data from 36 subjects were experimentally collected from the Zhongguancun metro station wayfinding model and Haidian Huangzhuang wayfinding data, and 36 groups of effective data were collected.

4.1 Wayfinding efficiency

The average wayfinding time of the subjects in the Zhongguancun metro station model was 198 seconds; in the Haidian Huangzhuang model, it was 344 seconds. The comparison revealed that the subject's wayfinding time was longer in Haidian Huangzhuang.

In the real-life wayfinding process, the time for wayfinding at the Zhongguancun metro station was only 151 seconds. The time spent at Haidian Huangzhuang station was 212 seconds. The results show that the time subjects spent finding their way was 31% longer (47 seconds) in Zhongguancun Station's 3D model and 62% (132 seconds) longer in Haidian Huangzhuang Station's 3D model.

A comparison of the model and real-life wayfinding data reveals that the actual wayfinding time was less than the time used in the model, whereas the actual wayfinding distance was the same, and the speed of actual wayfinding was faster than the speed in the model; thus, the efficiency of actual wayfinding was greater than the model wayfinding. The reason for this was that, on the one hand, the wayfinding model removed all kinds of elements, such as guide signs, and expressed only the spatial layout of the station, which made it more difficult for the subjects to find their way compared with real-life wayfinding. On the other hand, the subject's familiarity with the 3D software was not optimal, and there was a certain degree of delay in finding their way in the model.

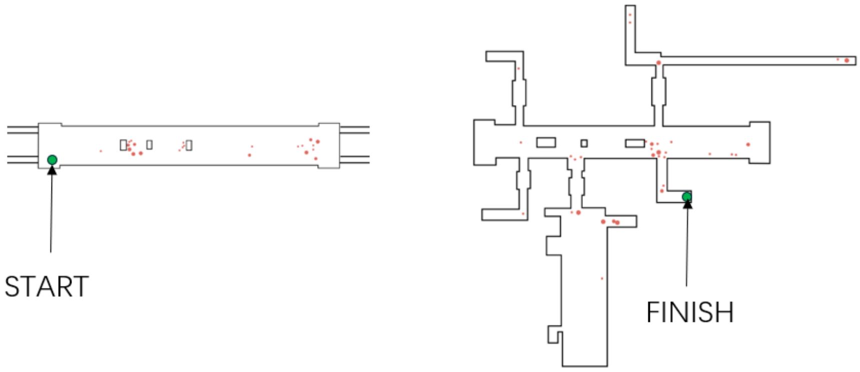

Figure 6 – Subject's hesitation points in the 3D virtual model of Zhongguancun Station

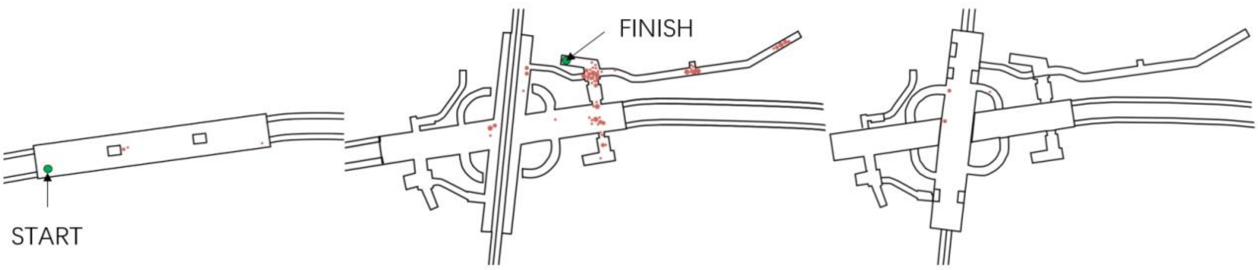

Figure 7 – Subject's hesitation points in the 3D virtual model of Haidian Huangzhuang Station

The subjects' hesitation points (the locations where the subject stayed for more than 2 seconds to find their way were recorded) in the 3D virtual model of Zhongguancun Station and Haidian Huangzhuang Station were also drawn during their wayfinding task (see *Figure 6* and *Figure 7*). The data of the subjects who lost their way were eliminated. It was difficult to tell the exact timestamp of when they started to get lost, because it could be easily mistaken for they were just trying to find the right direction. Furthermore, the time points are subdivided into three categories: 2–3 seconds, 3–5 seconds and 5 seconds or more. The longer the hesitation time, the larger the corresponding point size in the map.

It is found that in the 3D virtual blank model, the subjects tend to stay at key locations such as intersections, entrances, exits and road ends in the process of wayfinding upon in-depth analysis. The possible root cause is that these key points themselves have the problem of insufficient spatial guidance in the model. However, few passengers stop there in the real-life wayfinding process, and this indicates that the signage can effectively alleviate the problem of insufficient spatial orientation function to a certain extent. However, this does not mean that the space design itself has reached an ideal state, but that the signage temporarily compensates for the defects of the space design in the current situation. Therefore, further analysis (see section 4.3) was required to understand where, what and how the space design was flawed and needed improvement.

4.2 Wayfinding disorientation propensity

If the subjects did not find the exit within 10 minutes, they were considered to be lost in the model. In the experiment, it was found that particular subjects are more likely to get disoriented than others. According to the data, among 36 wayfinding subjects at Zhongguancun Station, 4 people were disoriented, accounting for 11% of the total number of subjects; among 36 wayfinding subjects at Haidian Huangzhuang Station, 10 people were disoriented, accounting for 28% of the total number of subjects.

Other than having no guidance-oriented element in the model, certain subjects in the experiment were not proficient in the operation of the 3D model, which has a certain impact on the wayfinding behaviour in the model. The reason for the lower disorientation rate in Zhongguancun Station is that it is an ordinary metro station, while Haidian Huangzhuang Station is a two-line transfer station with a more complex space layout than that of Zhongguancun, and this increases the difficulty of finding the way in Haidian Huangzhuang Station.

4.3 Subjective investigation

This part compared the actual real-life wayfinding data with the wayfinding data in the model, evaluated the efficiency of various types of spatial elements, and discovered the spatial layout problems in the spatial design of the station. The subjective evaluation was categorised into three categories through the questionnaire data: poor and in urgent need of improvement, average and in need of improvement, and good and not in need of improvement.

Transfer space quality evaluation

1) Establishment of the evaluation system

This experiment combined qualitative and quantitative evaluation, and the two experimental methods complement each other. Qualitative evaluation refers to a highly subjective evaluation system based on the research team's or individual's evaluation of the efficiency of space use or the quality of the surrounding environment. Its advantage is that it can intuitively show the subjective psychological state of the subjects, has a certain degree of flexibility and diversity, and reflects humanisation. A quantitative evaluation is a research team or individual based on the objective characteristics of things to rationally analyse and organise, obtain scientific data, and then carry out an evaluation and research. Quantitative evaluation deduces conclusions through deduction, and its results have strong stability and objectivity; the results are generally more convincing but more abstract. The combination of qualitative evaluation and quantitative evaluation effectively improves the logic and humanisation of the experimental results and has better persuasive power. This experiment was based on quantitative evaluation, assisted by qualitative evaluation.

After the wayfinding experiment, surveys based on the results of the questionnaire were carried out to understand the subjects' feelings toward the overall 3D spatial layout of urban metros, spatial design and path planning. The study applied a Likert scale to quantitatively record subject feelings, which was divided into 12 indicator layers, and each indicator was divided into 0–7 grades, corresponding to "very poor", "poor", "relatively poor", "average", "relatively good", "good" and "very good", respectively. After the subjects evaluated the corresponding indicators, quantitative data were obtained.

Qualitative evaluation study

The system consists of 3 criterion layers and 12 indicators, as shown in *Table 1*. The 3 criteria are “B1 General spatial layout” (with indicators C1–1 to C1–5), “B2 General spatial design” (with indicators C2–1 to C2–4) and “B3 Path planning” (with indicators C3–1 to C3–3). The final evaluation results can be divided into 3 categories, namely:

1) Category 1: When the average score of the actual real-life wayfinding (AW-S) is smaller than the wayfinding in the model (MW-S) and the ranking of the actual wayfinding (AW-R) is lower than or equal to the wayfinding in the model (MW-R), this category (AW-S < MW-S and AW-R=< MW-R) is evaluated as “poor, in urgent need of improvement”. The evaluation system of transfer space efficiency represents the urgency of updating and renovation.
2) Category 2: When the average score of the actual wayfinding is smaller than the wayfinding in the model (AW-S < MW-S) and the ranking of the actual wayfinding is higher than that of the wayfinding in the model (AW-R > MW-R), or when the average score of the actual wayfinding is larger than that of the wayfinding in the model (AW-S > MW-S) and the ranking of the actual wayfinding is lower than that of the wayfinding in the model (AW-R< MW-R), then the evaluation result is “average, needs to be improved”.
3) Category 3: When the average score of the actual wayfinding is greater than that of the wayfinding in the model (AW-S > MW-S) and the ranking of the actual wayfinding is greater than or equal to that of the wayfinding in the model (AW-R >= MW-R), the evaluation of the indicator in this category is “good, no need to improve”.

Table 1 – Evaluation indices of metro interchange space efficiency

Goal level	Guideline level	Indicator level
Evaluation of interchange space efficiency in urban metro	B1 General spatial layout	C1-1 Degree of diversity of spatial forms
		C1-2 Spatial guidance
		C1-3 Degree of spatial comfort
		C1-4 Degree of openness of spatial boundary
		C1-5 Degree of integration of spatial forms
	B2 General spatial design	C2-1 Interface design of regional borders
		C2-2 Clarity of regional division
		C2-3 Degree of regional visual connection
		C2-4 Nodal space design
	B3 Path planning	C3-1 Path accessibility
		C3-2 Path clarity
		C3-3 Path scale proportion

The analysis of the questionnaire data in *Table 2* reveals that in the actual Zhongguancun metro station scenario, the path accessibility, openness of spatial boundary and integration of spatial forms are “poor, in urgent need of improvement”; the path clarity, interface design of regional borders, clarity of regional division, nodal space design and regional visual connection are “average, in need of improvement”; and the path scale proportion, spatial comfort, spatial guidance and diversity of spatial forms are “good, not in need of improvement”.

Table 2 – Zhongguancun Station data

Indicator	Sample size	Actual wayfinding (via video) average score (AW-S)	Actual wayfinding (via video) ranking (AW-R)	Model wayfinding average score (MW-S)	Model wayfinding ranking (MW-R)	Change in score (delta S)	Change in ranking (delta R)	Spatial quality evaluation
C3-1 Path accessibility	36	4.58	3	5.08	1	-0.5	-2	Poor, in urgent need of improvement
C3-2 Path clarity	36	4.78	1	5	2	-0.22	1	Average, in need of improvement
C1-4 Degree of openness of spatial boundary	36	3.97	10	4.11	6	-0.14	-4	Poor, in urgent need of improvement
C1-5 Degree of integration of spatial forms	36	4.44	5	4..58	3	-0.14	-2	Poor, in urgent need of improvement
C2-1 Interface design of regional borders	36	3.5	12	3.47	11	0.03	-1	Average, in need of improvement
C2-2 Clarity of regional division	36	4.22	8	4.14	5	0.08	-3	Average, in need of improvement
C3-3 Path scale proportion	36	4.58	2	4.47	4	0.11	2	Good, not in need of improvement
C2-4 Nodal space design	36	3.78	11	3.61	10	0.17	-1	Average, in need of improvement
C1-3 Degree of spatial comfort	36	4.28	6	4.08	7	0.2	1	Good, not in need of improvement
C2-3 Degree of regional visual connection	36	4.19	9	3.97	8	0.22	-1	Average, in need of improvement
C1-2 Spatial guidance	36	4.44	4	3.89	9	0.55	5	Good, not in need of improvement
C1-1 Degree of diversity of spatial forms	36	4.25	7	3.25	12	1	5	Good, not in need of improvement

In the Haidian Huangzhuang Station scenario, the path accessibility and path clarity are “poor and in urgent need of improvement”; the openness of spatial boundary, integration of spatial forms and path scale proportion are “average, in need of improvement”; and the interface design of regional borders, clarity of regional division, nodal space design, spatial comfort, regional visual connection, spatial guidance and diversity of spatial forms are “good, not in need of improvement”, as shown in *Table 3*.

Table 3 – Data from the Haidian Huangzhuang Station

Indicator	**Sample size**	**Actual wayfinding (via video) average score (AW-S)**	**Actual wayfinding (via video) ranking (AW-R)**	**Model wayfinding average score (MW-S)**	**Model wayfinding ranking (MW-R)**	**Change in score (delta S)**	**Change in ranking (delta R)**	**Spatial quality evaluation**
C3-1 Path accessibility	36	4.03	5	4.39	1	-0.36	-4	Poor, in urgent need of improvement
C3-2 Path clarity	36	4.25	2	4.31	2	-0.06	0	Poor, in urgent need of improvement
C1-4 Degree of openness of spatial boundary	36	3.75	12	3.58	7	0.17	-5	Average, in need of improvement
C1-5 Degree of integration of spatial forms	36	3.86	10	3.67	5	0.19	-5	Average, in need of improvement
C2-1 Interface design of regional borders	36	4.28	1	4.08	3	0.2	2	Good, not in need of improvement
C2-2 Clarity of regional division	36	4.17	3	3.89	4	0.28	1	Good, not in need of improvement
C3-3 Path scale proportion	36	3.78	11	3.44	10	0.34	-1	Average, in need of improvement
C2-4 Nodal space design	36	3.86	9	3.47	9	0.39	0	Good, not in need of improvement
C1-3 Degree of spatial comfort	36	4	6	3.61	6	0.39	0	Good, not in need of improvement
C2-3 Degree of regional visual connection	36	3.94	7	3.5	8	0.44	1	Good, not in need of improvement
C1-2 Spatial guidance	36	3.89	8	3.25	11	0.64	3	Good, not in need of improvement
C1-1 Degree of diversity of spatial forms	36	4.11	4	3.03	12	1.08	8	Good, not in need of improvement

Zhongguancun Station has 3 “poor and in urgent need of improvement” indicator results, 5 “average, in need of improvement” indicator results and 4 “good, not in need of improvement” indicator results; Haidian Huangzhuang Station has 2 “poor and in urgent need of improvement” indicator results, 3 “average, in need of improvement” indicator results and 7 “good, not in need of improvement” indicator results.

Upon analysis, it can be concluded that Haidian Huangzhuang Station has relatively high space quality because of better and humanised spatial design, such as a good diversity of spatial forms, spatial guidance, visual connections and regional division, as well as interface designs as the transfer station of Line 4 and Line 10 to facilitate the convenient transfer of passengers.

When evaluating the quality of the transfer space, subjective evaluations of the transfer space with only architectural space information were compared with the transfer space with real-life information (space, interior decorations, signage, ads, etc.) quantitatively using the established space efficiency evaluation system. The score and ranking not only revealed the quality of the transfer space but also the specific spatial design aspects that need improvement to achieve better transfer efficiency and user satisfaction.

5. CONCLUSION

In this study, through a combination of virtual wayfinding experiments in transfer spaces inside 2 metro stations in Beijing and a follow-up questionnaire survey, the quality of the transfer space was evaluated. Quantitative analysis and subjective feelings were both used to discover the important factors affecting wayfinding efficiency and user satisfaction to identify the exact aspects that need optimisation in a station's architectural spatial design. The quantitative analysis includes the record of average wayfinding time, whereas the hesitation points during wayfinding inside the station's virtual 3D blank architecture model were also recorded. With the help of these parameters, an objective presentation of the wayfinding difficulty with only visual guidance from the architectural space of the station could be obtained. The subject's personal opinion of exactly what made them feel difficult to gain directional indications from the architectural space was also recorded with the help of questionnaires.

The transfer space quality evaluation system developed in this research work compares the average wayfinding time and personal opinions (using various indicators related to spatial design) on architectural spaces with the ones from real-life wayfinding situations inside the station to understand whether the current wayfinding difficulty was caused by the architectural spatial design and whether the lack of directional guidance of space was effectively compensated by the interior decorations and signage that was later installed. For instance, during our wayfinding experiment, we observed that the wayfinding efficiency was better in Zhongguancun Station than in Haidian Huangzhuang Station. However, the user satisfaction questionnaire rated the Haidian Huangzhuang Station overall to be higher than the Zhuangguancun Station, because its spatial form diversity, spatial guidance and regional visual connection, among others, are of good quality.

The authors consider the developed method for measuring transfer space quality using wayfinding efficiency and user satisfaction to be very useful for the great number of older metro stations in Beijing that are expecting to be "updated" to meet the passenger demand of the new era. The "to be updated" projects can vary in scale and size, namely from updating the signage system to a complete renovation of the station's spatial layout. To effectively save financial and time investment, the proposed method in this paper could be useful for designers when trying to identify which aspects in the station's architectural design were done correctly and should be maintained and which area were not done properly and should be improved in the later renovation work, thus providing more focused and insightful design suggestions.

6. FUTURE WORK

For future research, several directions can be explored to further enhance the understanding of wayfinding efficiency and user satisfaction in metro station transfer spaces.

Firstly, integrating more objective indicators is crucial. Currently, it is difficult to precisely identify information such as wrong turns, the exact location and the timestamp of getting lost due to the potential confusion with normal wayfinding behaviour. By using advanced tracking technologies like high-resolution video analytics (precisely record every turn and hesitation point) and wearable sensors (provide real-time data on a passenger's location, speed and even physiological responses related to stress during wayfinding, which may be associated with getting lost), these details can be accurately captured. The additional data will offer a more comprehensive view of the wayfinding process, enabling a deeper analysis of factors that influence efficiency.

Secondly, adapting the questionnaire indicators to be more accessible to the general public is essential. The current study requires experiment participants to have a certain knowledge of spatial perception, which limits the scope of participation. Simplifying the questionnaire language and using more intuitive and relatable concepts can encourage a wider range of people to participate. This way, individuals without a background in architecture or related fields can still provide valuable insights, making the results more representative of the general passenger population.

Finally, long-term studies should be carried out to monitor the effectiveness of design changes based on the current research findings. After implementing improvements in metro station transfer spaces, continuous monitoring over an extended period can reveal whether the changes have achieved the desired results in terms of wayfinding efficiency and user satisfaction. This can involve regularly collecting data on passenger flow, wayfinding times and feedback, and comparing it with pre-improvement data. Long-term studies will also help identify any potential long-term issues or unforeseen consequences of the design changes, allowing for further refinements and optimisations.

DECLARATION OF INTEREST

The authors report there are no competing interests to declare.

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